

A parabolic dish/AMTEC solar thermal power system and its performance evaluation

Shuang-Ying Wu^{a,*}, Lan Xiao^a, Yiding Cao^b, You-Rong Li^a

^a College of Power Engineering, Chongqing University, Chongqing 400044, China

^b Department of Mechanical and Materials Engineering, Florida International University, Miami, FL 33174, USA

ARTICLE INFO

Article history:

Received 19 May 2009

Received in revised form 5 August 2009

Accepted 27 August 2009

Available online 23 September 2009

Keywords:

Solar dish collector

AMTEC

Thermal to electric conversion

Efficiency

Parametric analysis

Solar thermal power system

ABSTRACT

This paper proposes a parabolic dish/AMTEC solar thermal power system and evaluates its overall thermal–electric conversion performance. The system is a combined system in which a parabolic dish solar collector is cascaded with an alkali metal thermal to electric converter (AMTEC) through a coupling heat exchanger. A separate type heat-pipe receiver is selected to isothermally transfer the solar energy from the collector to the AMTEC. To assess the system's overall thermal–electric conversion performance, a theoretical analysis has been undertaken in conjunction with a parametric investigation by varying relevant parameters, i.e., the average operating temperature and performance parameters associate with the dish collector and the AMTEC. Results show that the overall conversion efficiency of parabolic dish/AMTEC system could reach up to 20.6% with a power output of 18.54 kW corresponding to an operating temperature of 1280 K. Moreover, it is found that the optimal condenser temperature, corresponding to the maximum overall efficiency, is around 600 K. This study indicates that the parabolic dish/AMTEC solar power system exhibits a great potential and competitiveness over other solar dish/engine systems, and the proposed system is a viable solar thermal power system.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Due to energy and environment problems, as well as increasing demand for electricity, the conversion of solar energy into electricity is receiving more and more attention in recent years. Sunlight is the world's largest energy source and the amount that can be readily accessed with existing technology greatly exceeds the world's primary energy consumption. Furthermore, sunlight is free, clean, renewable and technically exploitable in most part of the inhabited earth [1]. Today, two major solar energy technologies, photovoltaic and solar thermal power (electric), are being actively developed for electricity production. Photovoltaic, also referred to as solar voltaic, is the direct conversion of solar radiation to electricity using photovoltaic materials. Solar thermal power (electric), also referred to as concentrating solar power, is electricity production from heat generated by solar radiation, e.g. via heat exchangers and steam turbines. Restricted by the capital cost of solar panels and other issues, the photovoltaic technology is being increasingly challenged by solar thermal power technology [2,3]. In recent years, a number of solar thermal power plants have been installed in countries such as the US, Europe, India, and China [4,5].

Solar thermal power systems utilize the heat generated by concentrating and absorbing the sun's energy to drive a heat engine/generator and produce electric power. Three generic solar thermal

power systems, trough, power tower, and dish/engine systems, are being employed for power production [6,7]. Trough systems use linear parabolic concentrators to focus sunlight along the focal lines of the collectors. In a power tower system, a field of two-axis tracking mirrors, called heliostats, reflects the solar energy onto a receiver that is mounted on top of a centrally-located tower. Dish/engine systems, the third type of solar thermal power system, comprise a parabolic dish concentrator, a thermal receiver, and a heat engine/generator located at the focus of the dish to generate power. Of the three solar thermal power technologies, trough–electric systems are the most mature. They have a sun concentration ratio of about 75 and operate at temperatures of around 400 °C at an annual efficiency of about 10% [8]. Power towers operate at a concentration ratio of around 800 and temperatures of about 560 °C and have annual efficiencies of about 15%. Dish/engine systems are characterized by high efficiency, modularity, autonomous operation, and an inherent hybrid capability (the ability to operate on either solar energy or a fossil fuel, or both). A number of thermodynamic cycles and working fluids have been considered for dish/engine systems. These include Rankine cycles, using water or an organic working fluid; Brayton cycles, both open and closed cycles; and Stirling cycles. Among these, Stirling engines have been mainly used and developed in the US and Europe [9,10]. The dish/Stirling systems seem potential to become one of the least expensive sources of renewable energy due to their high solar-to-electric conversion efficiency (29.4% reported in 1984 [11], and a new record of 31.25% in 2007 [12]).

* Corresponding author. Tel.: +86 23 65112284; fax: +86 23 65102473.

E-mail address: shuangyingwu@yahoo.com.cn (S.-Y. Wu).

[illegible]

A way to alleviate the problems discussed above is using a new power conversion unit (PCU)—alkali metal thermal to electric converter (AMTEC) with dishes. The AMTEC is a thermally regenerative electrochemical device for the direct conversion of heat to electrical energy [14]. It has many inherent advantages over conventional forms of electric generation, such as high efficiency (20–40%) [15], high density (up to 0.5 kW/kg) [16], absence of moving parts, good reliability, maintenance-free, modular design, competitive manufacturing costs, and compatible with many heat and fuel sources, including radioisotope, concentrated solar, external combustion, and nuclear reactor etc. Especially, the operating temperature (900–1300 K) and rated output power (several to 50 kW) of the AMTEC perfectly matches the parabolic dish collector system.

Furthermore, from the viewpoint of economic performance, AMTEC might provide significant cost savings for solar thermal to electricity generation. Take the dish/Stirling system as an example for comparison; the costs for a Stirling Energy Systems' (SES) dish/Stirling system with rated output of 25 kW are high at about 10,000 \$/kW [9]. And the PCU in the SES' dish/Stirling system costs 33%, i.e., 3300 \$/kW. As reported in [17], the cost of AMTEC was estimated to be in the range between 1000 \$/kW and 2000 \$/kW, which is 2300–1300 \$/kW lower than that of PCU in the SES' dish/Stirling system. This preliminary economic comparison shows that adopting AMTEC as a PCU is expected to create more profit.

Therefore, a parabolic dish/AMTEC solar thermal power system comprised of a parabolic dish solar collector and an AMTEC is put forward in this paper. These two subsystems are thermally coupled by a heat exchanger, where the useful energy collected in the solar collector subsystem is delivered to the AMTEC subsystem. The parabolic dish solar collector system consists of a dish concentrator, and a receiver located at the focal point of the dish. Existing literatures have shown that both the measured and calculated total heat losses from the receiver, including conductive, convective, and radiative losses at higher operating temperatures are much more than those at lower operating temperatures [18,19]. That is to say, for a given type of collector, the higher the operating temperature, the lower thermal efficiency of the collector. On the other hand, for the AMTEC, the higher the temperature at which heat is supplied, the higher the conversion efficiency of the power cycle [20]. Hence, the overall conversion efficiency of the parabolic dish/AMTEC solar thermal power system is related to the operating temperature of the coupling heat exchanger, and an optimal operating temperature of the coupling heat exchanger should exist.

In this paper, a study on the thermal–electric conversion performance of the proposed system is presented. And this paper focuses on investigating the optimal operating temperature corresponding to the peak efficiency of the dish/AMTEC system, in conjunction with a parametric analysis on the overall conversion efficiency. This analysis is developed in four successive steps: first a simplified system is demonstrated, then a theoretical analysis model for calculating the system overall conversion efficiency is developed, afterwards validation of the analysis model is performed, and finally a parameter investigation is conducted.

2. The description of the parabolic dish/AMTEC solar thermal power system

As indicated in Fig. 1, the dish/AMTEC solar thermal power system comprises a parabolic dish solar collector subsystem and a power conversion subsystem—AMTEC. The two subsystems are thermally coupled by a heat exchanger, where the useful energy collected in the solar collector subsystem is delivered to the AMTEC subsystem.

The parabolic dish solar collector system is a point-focus collector that tracks the sun in two axes. The size of the dish concentrator is determined by the AMTEC output power requirement. A separate type high temperature heat-pipe receiver is employed in this proposed system. Heat-pipe receiver technology has demonstrated significant performance enhancements to an already efficient dish/Stirling power conversion module [21]. In the meantime, the orientation of absorber (evaporator) of this separate type heat-pipe receiver is adjustable to efficiently receive solar rays from the dish during its rotation, while the condenser can be kept static. This characteristic of the receiver makes the configuration more flexible. As shown in Fig. 1, the receiver has three components, including a cylinder cavity, an absorber (evaporator),

and a condenser which also operates as the coupling heat exchanger. It is obvious that the coupling heat exchanger operates (functions) as both the condenser of the separate type heat-pipe receiver and the evaporator of the AMTEC. The diameter of the cylinder cavity is larger than its length so as to improve the absorption of solar energy and reduce parasitic heat losses. Sodium metal is employed as working fluid to isothermally transfer heat from the heat-pipe receiver to the AMTEC through the coupling heat exchanger. This results in a uniform temperature in the coupling heat exchanger, thereby enabling a higher working temperature for a given material and therefore higher AMTEC efficiency. In order to achieve the temperatures required (900–1300 K) to efficiently convert thermal energy into electricity, the concentration ratio of the collector is typically more than 2000. To satisfy such a high operating temperature, structural materials should be carefully selected. Experimental evidence has suggested that up to 800–850 °C, stainless steel is an adequate material, while for higher temperatures, up to 1200 °C, refractory metals (niobium, molybdenum, tantalum), or refractory alloys, such as niobium alloys Nb–1Zr (1%Zr) and molybdenum–rhenium (Mo–41%Re) should be used [17,22].

The AMTEC subsystem consists of numbers of β'' -alumina solid electrolyte (BASE) elements connected to improve the power output, because one BASE element provides relatively low voltage (~ 0.7 V). The BASE elements divide the AMTEC into two regions, which are the high temperature region with an evaporator and the low temperature region with a condenser. There are two types of evaporator applied in the AMTEC system. One is tube evaporator, which may employ an electromagnetic pump to circulate the working fluid from the condenser to the evaporator, as shown in Fig. 1a. The other type is shown in Fig. 1b, a capillary evaporator based on the principle of the capillary pumped loop (CPL) is employed.

The operation principle of the system is as follows: The dish-shaped concentrator reflects and concentrates incoming direct normal insolation to a receiver located at the focal point of the dish. Inside the receiver, the liquid sodium metal is vaporized by the intense heat created by the concentrated sunlight on the back surface of the cavity, on which a distributed capillary wick is covered. The generated sodium vapor flows up and condenses in the coupling heat exchanger, where it gives out the evaporation latent heat to the working fluid (sodium or potassium, here sodium is adopted as an example) in the AMTEC. The resulting liquid sodium of the heat-pipe receiver is returned to the absorber (evaporator) by electromagnetic pump or passively by gravity, which can be achieved by the height difference between the coupling heat exchanger and receiver, and capillary forces in a distributed wick.

On the other hand, the liquid sodium in the AMTEC subsystem absorbs the heat released by the sodium vapor in the heat-pipe receiver loop, and becomes high temperature and high pressure vapor, and then is introduced into the AMTEC's hot region. Due to the thermodynamic potential across the BASE, ionization of sodium metal occurs at the anode/BASE interface. The sodium ions diffuse through the BASE to the cathode due to the pressure difference across the BASE. The electrons circulate through the external load producing electrical work and then reach the cathode/BASE interface where they recombine with the sodium ions. The neutral sodium then reaches the condenser surface, where it gives up the latent heat of condensation to become liquid. The resulting liquid metal is circulated back by an electromagnetic pump (Fig. 1a) or capillary action (Fig. 1b) to the coupling heat exchanger (the evaporator of the AMTEC). The cycle is thus repeated, and the AMTEC converts the work of isothermal expansion of sodium vapor in BASE elements directly to electric power [16].

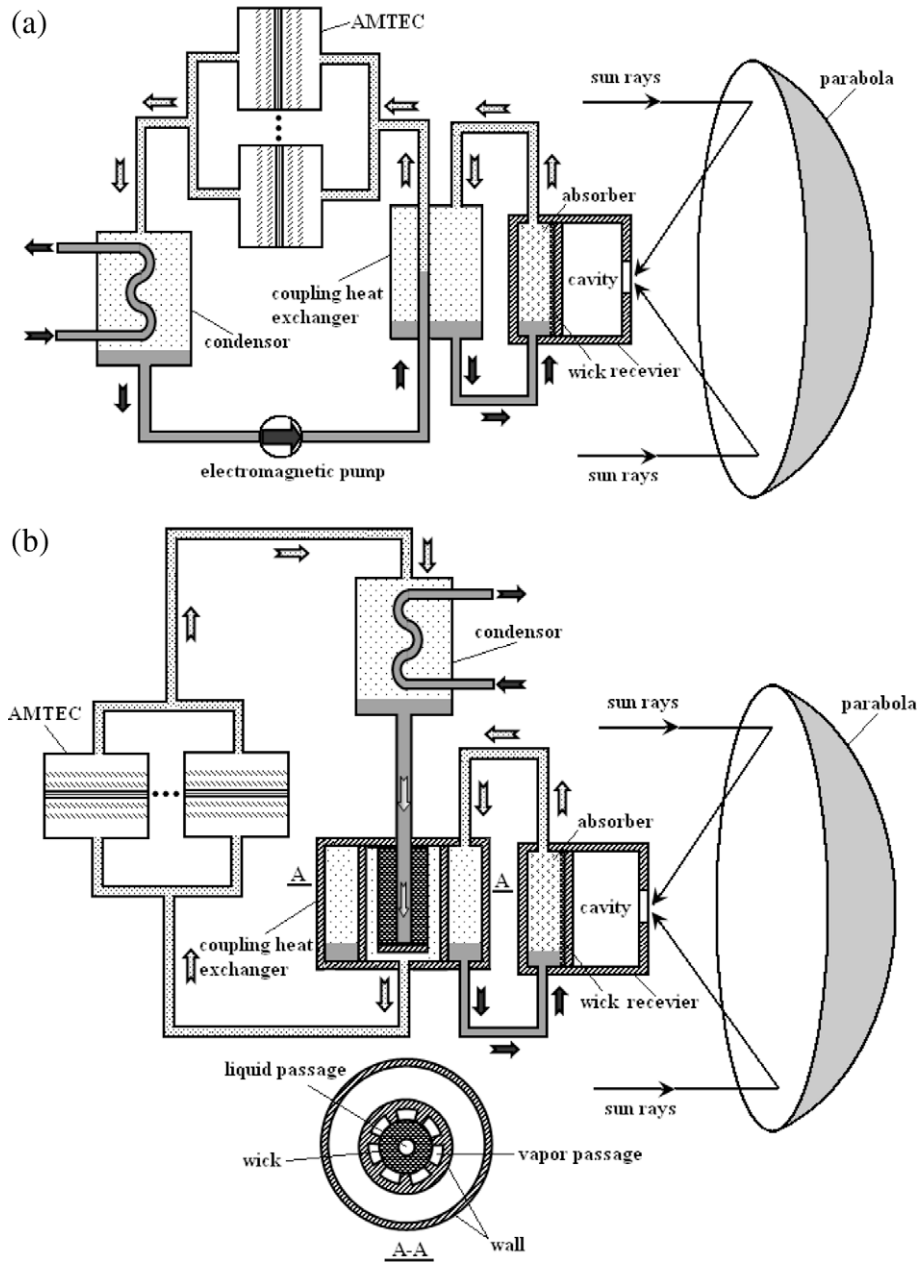


Fig. 1. The parabolic dish/AMTEC solar thermal power system; (a) the combined system based on electromagnetic pump; (b) the combined system based on capillary pumped loop.

3. Thermal–electric conversion efficiency of the parabolic dish/AMTEC solar thermal power system

The overall conversion efficiency of the solar thermal power system is defined as the ratio of the output electric power of the AMTEC to the energy incident on the dish concentrator aperture of the solar collector. It is the product of the solar collector thermal efficiency η_c and the thermal–electric conversion efficiency of the AMTEC η_{AMTEC} ,

$$\eta_{overall} = \eta_c \eta_{AMTEC} \quad (1)$$

The thermal efficiency of the parabolic dish solar collector subsystem and the thermal–electric conversion efficiency of AMTEC subsystem are analyzed as follows, respectively.

3.1. Thermal efficiency of the parabolic dish solar collector subsystem

The collector thermal efficiency is defined as the ratio of the useful energy delivered to the energy incident on the concentrator aperture [1]. Namely,

$$\eta_c = Q_u / Q_s \quad (2)$$

Consider that the dish concentrator has an aperture area A_a and receives solar radiation at the rate Q_s from the sun, as shown in Fig. 2. The net solar heat transferred Q_s is proportional to A_a , and the direct normal insolation (DNI) per unit of collector area I_s , which varies with geographical position on the earth, the orientation of the dish concentrator, meteorological conditions and the time of day. In the present analysis, I_s is assumed to be constant and the system is in steady state, i.e.

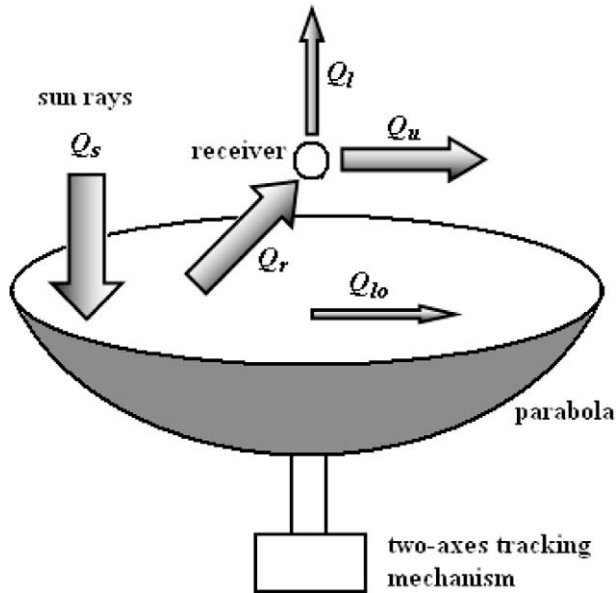


Fig. 2. Parabolic dish collector model.

$$Q_s = I_s A_d \quad (3)$$

Under steady state conditions, the useful heat delivered by a solar collector system is equal to the energy absorbed by the heat transfer fluid, which is determined by the radiant solar energy falling on the receiver minus the direct or indirect heat losses from the receiver to the surroundings. That is,

$$Q_u = Q_r - Q_l \quad (4)$$

The radiation falling on the receiver Q_r is a function of the optical efficiency η_o , which is defined as the ratio of the energy falling on the receiver to the energy incident on the concentrator's aperture. And the receiver efficiency η_r is defined as the ratio of the useful energy delivered to the energy falling on the receiver [1]. That is

$$\eta_o = Q_r / Q_s \quad (5)$$

$$\eta_r = Q_u / Q_r \quad (6)$$

Combining Eqs. (2), (4)–(6), the collector thermal efficiency can be written as

$$\begin{aligned} \eta_c &= \frac{Q_u}{Q_s} = \frac{Q_r}{Q_s} \cdot \frac{Q_u}{Q_r} = \eta_o \cdot \eta_r = \eta_o \cdot \frac{Q_r - Q_l}{Q_r} = \eta_o \left(1 - \frac{Q_l}{Q_r}\right) \\ &= \eta_o \left(1 - \frac{Q_l}{\eta_o Q_s}\right) = \eta_o - \frac{Q_l}{Q_s} \end{aligned} \quad (7)$$

where Q_l is the total heat loss rate of the receiver. In order to determine the thermal efficiency of the collector, the optical efficiency η_o and the total heat loss rate of the receiver Q_l should be obtained.

3.1.1. The optical efficiency η_o

The optical efficiency η_o depends on the optical properties of the materials involved (e.g. the reflectance of dish and the optical properties of the receiver glazing etc.), the geometry of the collector, and the various imperfections arising from the construction of the collector. It can be analyzed by identification of the different losses mechanisms [23,24].

- Cosine loss—quotient of total reflective area and its projected area, as seen from the sun.
- Shading loss—part of the reflective area of the dish is shadowed by the receiver, which is located at the focal point of the dish. But this shading can be kept a minimum if the dish

aperture size is much larger than the receiver, generally, less than 1% shading [23].

- Reflectivity loss—quotient of reflected energy and energy impinging on the reflective dish surface. A clean mirror made of low-iron glass with a silver back-coat should provide a reflectivity of 90–94% [23].
- Transmission–absorption loss—energy is lost through transmission of the reflected sunlight in the air from dish to the receiver, causing about 2–4% loss [23]; on the other hand, fraction of reflected radiation hitting the receiver cavity surface is absorbed. An ideally insulated, isothermal receiver, without a transparent window at the receiver entrance, can be considered as a blackbody with the effective absorptance of one [25,26]. In this study, a transparent window is placed at the receiver entrance to block off dust and wind, hence the effective absorptance of the receiver is assumed to have about 5–8% loss. Namely, these would cause a total of 7–12% loss.
- Spillage—fraction of radiation arriving outside the entrance aperture of receiver may cause about 1–3% additional loss [9].

Therefore, the following equation form can be used to perform an approximated optical efficiency analysis,

$$\eta_o = \lambda \rho \tau \alpha \gamma \cos(\theta) \quad (8)$$

where λ is the factor of un-shading, ρ is dish reflectance, $\tau\alpha$ is transmittance–absorptance product, γ is the intercept factor of receiver, which is defined as the ratio of the energy intercepted by the receiver to the energy reflected by the focusing device, i.e. parabola dish, θ is angle of incidence. As the solar parabolic dish concentrator maintains its optical axis always pointing directly towards the sun to reflect the beam, which means the incidence angle of solar beam into the dish is zero degree, and the cosine loss equals to zero [27]. The Eq. (8) can be written as

$$\eta_o = \lambda \rho \tau \alpha \gamma \quad (9)$$

Based on the analysis above, the optical efficiency used in the current study, including all of these losses, is then assumed as a value of 0.83, which is close to the representative value of 0.85 reported in [23,24].

3.1.2. The total heat loss rate of the receiver Q_l

The total heat loss rate of the receiver Q_l includes three contributions: (i) conductive heat loss from receiver, Q_{lk} , (ii) convective heat loss through the receiver aperture, Q_{lc} , and (iii) radiative heat loss through the receiver aperture, Q_{lr} . The total heat loss rate Q_l can be expressed as:

$$Q_l = Q_{lk} + Q_{lc} + Q_{lr} \quad (10)$$

The outer surface of the receiver is usually covered with a thick blanket of opaque insulation to reduce the conductive heat loss. Research has showed that the conductive loss is normally insignificant compared to the convection and radiation losses [18,28]. Therefore, in this study, the outer walls of the receiver are assumed to be adiabatic and the conductive heat loss from receiver $Q_{lk} = 0$.

Among the various modes of heat loss mentioned above, convection is the most complicated phenomenon and yet also a major contributor of the total energy loss. Hence, its characteristic has been extensively investigated so as to find out effective measurements for the improvement of system efficiency. Many authors have proposed models to predict convection heat loss of cavity receivers, such as Le Quere et al. model [29], Koenig and Marvin model [30], Siebers and Kraabel model [31], Clausing model [32], modified Clausing model [18], Stine and McDonald model [33], modified Stine and McDonald model [18], Paitoonsurikarn et al. model [34] etc. It should be noted that most models were established to

evaluate the natural convection heat loss, while the effect of wind was not considered. For the models mentioned above, Clausing model shows the closest prediction for downward-facing cavity receivers despite its original use for bigger-scale central receivers [35]. However, Clausing model is inconvenient to use because it is implicit. The simpler explicit correlation, modified Stine and McDonald model gave slightly better results than the implicit modified Clausing model [18]. Consider that the receiver in this study has similar geometry and operating conditions with the receiver researched by Stine and McDonald, the modified Stine and McDonald model is selected to estimate the receiver's convection heat loss while the influence of wind is neglected. Because in this study, a transparent window is installed at the receiver aperture to block off dust from the air, which also prevents forced convection flow to some extent, thus natural convection heat loss becomes the dominant loss. The modified relation of the angle dependent function $h(\varphi)$ in [34] is adopted. It follows that

$$Nu_L = 0.106 Gr_L^{1/3} (T_w/T_a)^{0.18} (4.256 A_c/A_w)^s h(\varphi) \quad (11)$$

$$\text{where } Gr_L = g\beta(T_w - T_a)L^3/\nu^2 \quad (12)$$

$$s = 0.56 - 1.01(A_c/A_w)^{1/2} \quad (13)$$

$$h(\varphi) = 1.1677 - 1.0762 \sin(\varphi^{0.8324}) \quad (14)$$

In our case, the characteristic length of the receiver is the diameter of the cavity, D . All properties are taken at film temperature, i.e., the average of receiver's cavity wall temperature and ambient temperature.

The convective heat transfer coefficient can be expressed as:

$$h_c = Nu_L k/L \quad (15)$$

The convective heat loss from the receiver is given as:

$$Q_{lc} = h_c A_w (T_w - T_a) \quad (16)$$

Because the receiver of a parabolic dish collector system typically has very small entrance aperture area A_c compared to the receiver's internal cavity area A_w , which results in less radiation loss. And the entrance aperture area A_c is related to the geometric concentration ratio C , which is defined as the ratio of dish concentrator aperture area to the receiver's entrance aperture area. The following equation is used to evaluate the radiation loss from the receiver [36],

$$Q_{lr} = A_c \varepsilon_{\text{eff}} \sigma (T_w^4 - T_a^4) \quad (17)$$

$$\text{where } \varepsilon_{\text{eff}} = 1 / \left[1 + \left(\frac{1}{\varepsilon_c} - 1 \right) \frac{A_c}{A_w} \right] \quad (18)$$

$$A_c = A_a / C \quad (19)$$

According to the results from [37], the effective infrared emittance of cavity ε_{eff} is almost equal to 1 when the cavity surface emittance ε_c is in the range of 0.8–1 and the geometrical parameter (A_w/A_c) of the focal receiver is larger than 5. Thus, the assumption of black body for calculating radiative heat loss through the receiver aperture is reasonable.

3.2. The conversion efficiency of the AMTEC subsystem

In reality, there exists a temperature difference ΔT_{w-hp} between the average operating wall temperature in the cavity T_w and the evaporative temperature in the heat-pipe absorber $T_{ev, hp}$ due to the fact that the solar energy is continuously transferred to sodium in the absorber. Similarly, the evaporative temperature in the heat-pipe absorber $T_{ev, hp}$ is greater than the evaporative temperature in the coupling heat exchanger (evaporator of AMTEC power cycle) T_{ev} , whose temperature difference is ΔT_{hp-ev} . Therefore, we have

$$T_w = T_{ev} + \Delta T_{w-hp} + \Delta T_{hp-ev} \quad (20)$$

In general, the value of $\Delta T_{w-hp} + \Delta T_{hp-ev}$ is less than 50 K, which is much smaller compared to the working temperature T_w and T_{ev} for the combined system. On the other hand, it is assumed that BASE temperature T_B is equal to the evaporative temperature T_{ev} when the heat dissipation from the coupling heat exchanger to BASE elements is neglected. Therefore, for convenience, it follows from above assumptions that $T_B = T_{ev} = T_w$.

The conversion efficiency of the AMTEC is defined as the ratio of net output electric power to all the required heat input, presented by the electrochemical work produced by the alkali metal ions' isothermal expansion through the BASE elements at T_B , the total heat absorbed by the working fluid to change from liquid sodium at T_{cd} to vapor sodium at T_{ev} , and the total parasitic heat losses, including the radiation loss, Joule heating and heat conduction loss of conductor leads etc. While neglecting the Joule heating and heat conduction loss of conductor leads, the consumed power of electromagnetic pump (if used), and the parasitic losses are presented by radiation loss $A_{eq, \text{rad}}$, the conversion efficiency of the AMTEC is calculated as [16]

$$\eta_{\text{AMTEC}} = \frac{J(V_o^{\text{cc}} - R_{\text{int}})}{J \ln(P_a/P_c^{\text{cc}})/f_B + [c_{pl}(T_B - T_{cd}) + h_{fg}(T_B)]JM/F + q_{\text{rad}}} \quad (21)$$

In order to calculate the effective electromotive force per BASE element V_o^{cc} , the pressure of sodium vapor at the BASE/anode interface, P_a , and BASE/cathode interface, P_c^{cc} , should be determined. According to the above assumption, the pressure of sodium vapor at the BASE/anode interface (the high pressure side) is equal to the saturation pressure at T_{ev} , namely, $P_a = P_{\text{sat}}(T_{ev})$. The pressure at the BASE/cathode interface, P_c^{cc} , is given by [38]

$$P_c^{\text{cc}} = P_c^{\text{oc}} + \Delta P_{cd} \quad (22)$$

where P_c^{oc} is the sodium vapor pressure at the BASE/cathode interface in open-circuit condition, given by $P_{\text{sat}}(T_{cd}) \sqrt{T_B/T_{cd}}$, where $P_{\text{sat}}(T_{cd})$ is the saturation pressure at the condenser temperature T_{cd} , and ΔP_{cd} is the total vapor pressure losses on the cathode side of the AMTEC, which is determined by [38]

$$\Delta P_{cd} = \frac{3G}{8\pi} (2\pi MR_g T_B)^{1/2} \frac{J}{F} \quad (23)$$

The effective electromotive force per BASE element V_o^{cc} , is given by [39]

$$V_o^{\text{cc}} = V^{\text{oc}} - \xi_a + \xi_c \quad (24)$$

where V^{oc} is the open-circuit electrochemical potential per BASE element, given by Nernst equation [16]

$$V^{\text{oc}} = \frac{R_g T_B}{F} \ln \left(\frac{P_a^{\text{oc}}}{P_c^{\text{oc}}} \right) = \frac{1}{f_B} \ln \left(\frac{P_a^{\text{oc}}}{P_c^{\text{oc}}} \right) \quad (25)$$

where P_a^{oc} is the sodium vapor pressure at the BASE/anode interface in open-circuit condition and is equal to the saturation vapor pressure at the evaporator temperature $P_{\text{sat}}(T_{ev})$.

The concentration and charge-exchange polarization overpotentials at the anode, ξ_a , and at the cathode, ξ_c , used in Eq. (24) are given by the Butler–Volmer equation [40,41]:

$$\frac{J_i}{J_i^{\text{ex}}} = \exp(-\alpha f_B \xi_i) - \frac{P_i^{\text{cc}}}{P_i^{\text{oc}}} \exp[(1 - \alpha) f_B \xi_i] \quad (26)$$

where the subscript “i” in Eq. (26) stands for either “a” (anode) or “c” (cathode). For a symmetric barrier, the electrochemical transfer coefficient $\alpha = 1/2$, and Eq. (26) can be inverted to give the polarization overpotential explicitly in terms of the current density:

$$\xi_i = -\frac{2}{f_B} \ln \left\{ \frac{1}{2} \left[\left(\frac{J_i}{J_i^{\text{ex}}} \right)^2 + 4 \frac{P_i^{\text{cc}}}{P_i^{\text{oc}}} \right]^{\frac{1}{2}} + \frac{1}{2} \frac{J_i}{J_i^{\text{ex}}} \right\} \quad (27)$$

The overpotential, ξ_i , increases logarithmically with the current, which reduces the voltage potential across the BASE. In Eq. (27), $\xi_c < 0$, $\xi_a > 0$, and $J_c = -J_a$ for a thin BASE membrane. The charge-exchange current densities J_i^{ex} , a measure of the effective local conductance at the BASE/electrode/sodium vapor triple phase boundary, are related to the saturated equilibrium charge-exchange current density $J_{\text{sat}}^{\text{ex}}$, as [40,41]:

$$J_i^{\text{ex}} = J_{\text{sat}}^{\text{ex}} \left[\frac{P_i^{\text{oc}}}{P_{\text{sat}}(T_B)} \right]^{1/2} \quad (28)$$

Since the sodium vapor pressure at the BASE/cathode interface (normally $P_c^{\text{cc}} < 100$ Pa) is several orders of magnitude smaller than that at the BASE/anode interface (normally $P_a^{\text{cc}} > 20$ kPa), the anode exchange-current density is much larger than the cathode exchange-current density, hence the polarization overpotential on the anode side ξ_a is negligible. Experimental investigations have shown that the saturated equilibrium exchange-current density, $J_{\text{sat}}^{\text{ex}}$, is essentially a function of the BASE temperature and of the type of electrodes. It can be expressed as [40,41]

$$J_{\text{sat}}^{\text{ex}} = B \frac{P_{\text{sat}}(T_B)}{\sqrt{T_B}} \quad (29)$$

Substituting Eq. (29) into Eq. (28), we have

$$J_i^{\text{ex}} = B [P_i^{\text{oc}} P_{\text{sat}}(T_B) / T_B]^{1/2} \quad (30)$$

The specific internal resistance per BASE element R_{int} , which is represented by the BASE ionic resistance R_B , has been given by [42]

$$R_B = \rho_B \delta_B \quad (31)$$

where ρ_B is determined by Steinbruck et al. [43].

$$\rho_B = 1.62 \times 10^{-5} T_B \exp(-45.5/T_B) + 1.55 \times 10^{-7} T_B \exp(3722/T_B) \quad (32)$$

The radiation heat loss from the BASE to the condenser and the wall surface is most significant compared to other parasitic heat loss, and expressed as

$$q_{\text{rad}} = \frac{\sigma}{Z} (T_B^4 - T_{\text{cd}}^4) \quad (33)$$

where Z is the geometric factor, given as [44]

$$Z = \frac{1}{\varepsilon_B} + \frac{1}{\varepsilon_{\text{cd}}} - 1 \quad (34)$$

where ε_B is radiative emissivity of BASE, typically 0.9 above 1100 K. And ε_{cd} is the radiative emissivity of condenser surface, which is coated with liquid sodium.

4. Validation of the analysis model

As the proposed parabolic dish/AMTEC solar thermal power system is only a conceptual design and has not been actually constructed in reality, therefore, no literature has been reported on the overall thermal–electric conversion performance of this new system. Fortunately, a few literatures have been published on the thermal performance of receiver and the AMTEC system. In this study, in order to evaluate the thermal performance of the parabolic dish collector system, the optical efficiency has been approximately estimated, and the focus has been put on the calculation of heat loss in the receiver. For the purpose of validating the analysis model discussed in Section 3, the case of an electrically heated model receiver with temperatures ranging from 450 °C to 650 °C reported by Taumoeolau et al. [35] was studied. The results of comparison are presented in Table 1. We can see that the deviations vary from –9.1% to 17.6% for the natural convection heat loss at $T_w = 450$ °C, from –13.4% to 23.7% at $T_w = 550$ °C, and from –23.5% to 26.2% at $T_w = 650$ °C, respectively. The relatively large deviations can be explained by two reasons. As indicated in [45], the calculated model adopted in this study is more accurate if the receiver has similar size to the data of actual receiver from which the model is derived. However, the fact is that the receiver experimentally studied in [35] was much smaller than the actual receiver size. The other reason is that the experimental results were obtained from an electrically heated model receiver in a controlled environment, which is different from the working condition of actual receivers. These two factors might together lead to the relatively large discrepancy. Nevertheless, the calculation results for the receiver considered in this study using the analysis model ought to be acceptable, because the receiver investigated in this study has similar size and working conditions with those of the derived receiver model.

For validating the calculation model of the AMTEC subsystem, the case in [14] was studied. The efficiency of AMTEC η_{AMTEC} varying with the BASE temperature T_B and condenser temperature T_{cd} was calculated using the model in Section 3. In [14], the cathode electrode was made of fine grain porous WRh_{1.5}, characterized by $B = 90 \text{ AK}^{1/2}/\text{Pa m}^2$, $G_E = 10$, the current density of the BASE electrodes was 0.29 A/cm². The results for η_{AMTEC} varying with T_B were obtained when T_{cd} was 645 K. The results for η_{AMTEC} varying with T_{cd} were obtained when T_B was 1127 K. The comparisons are presented in Tables 2 and 3. It is found that η_{AMTEC} varying with T_B in this study is about 3.6–9.5% lower than the results in [14]. Similarly, variation of η_{AMTEC} with T_{cd} is about 7.5–10.5% lower. The underestimations can be explained by the fact that, in [14], on top of BASE elements, thermal radiation shields were installed to reflect thermal radiation back towards the BASE elements, which reduced radiation heat loss in the low pressure cavity. For simplification, this has been neglected in this preliminary study. However, they show same trend and close results in the whole. Hence, the calculated model provided here can be used with confidence.

Table 1
Results comparison of convection heat loss from the receiver between the present analysis model and [35].

φ (°)	$T_w = 450$ °C			$T_w = 550$ °C			$T_w = 650$ °C		
	$Q_{\text{c,cal}}$ (W)	$Q_{\text{c,exp}}$ (W)	Error (%)	$Q_{\text{c,cal}}$ (W)	$Q_{\text{c,exp}}$ (W)	Error (%)	$Q_{\text{c,cal}}$ (W)	$Q_{\text{c,exp}}$ (W)	Error (%)
0	144.1	125.0	15.2	175.9	155.8	12.9	208.2	165.2	26.2
15	101.4	86.2	17.6	123.7	100.0	23.7	146.4	126.5	15.7
30	70.9	62.6	13.2	86.6	70.8	22.3	102.5	92.6	10.7
45	47.2	41.2	14.6	57.6	48.6	18.5	68.2	56.8	20.1
60	29.6	30.0	–1.3	36.2	38.2	–5.2	42.8	48.6	–11.9
75	18.0	19.8	–9.1	22.0	25.4	–13.4	26.0	30.8	–15.6
90	12.2	12.0	–1.7	14.8	15.2	–2.6	17.6	23.0	–23.5

Note: Subscript “c, cal” means the calculation results in this study, “c, exp” means the experimental results in [35].

Table 2Results comparison of η_{AMTEC} varying with T_B between the present analysis model and [14].

T_B (K)	η_{AMTEC} (%) in this study	η_{AMTEC} (%) in [14]	Error (%)
970	19.0	19.7	−3.6
1030	22.5	23.9	−5.9
1090	25.0	27.1	−7.7
1150	26.6	29.4	−9.5

Table 3Results comparison of η_{AMTEC} varying with T_{cd} between the present analysis model and [14].

T_{cd} (K)	η_{AMTEC} (%) in this study	η_{AMTEC} (%) in [14]	Error (%)
500	25.9	28.9	−10.4
550	26.2	29.1	−10.0
600	26.3	29.4	−10.5
650	26.0	28.9	−10.0
700	24.8	26.8	−7.5

5. Results and discussions

To demonstrate the effects of varying parameters on the overall thermal–electric conversion efficiency of the parabolic dish/AMTEC system, numerical calculations were conducted according to the analysis in Section 3. Note that all the results presented here are based on the main parameters of the combined system summarized in Table 4.

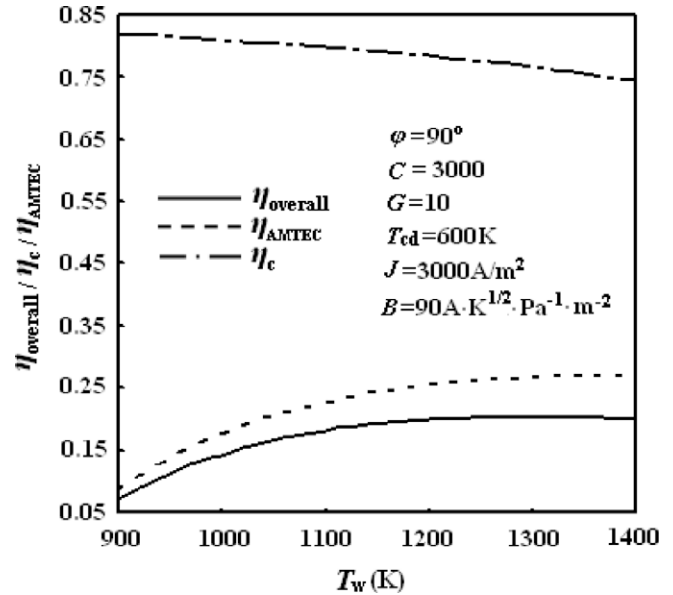
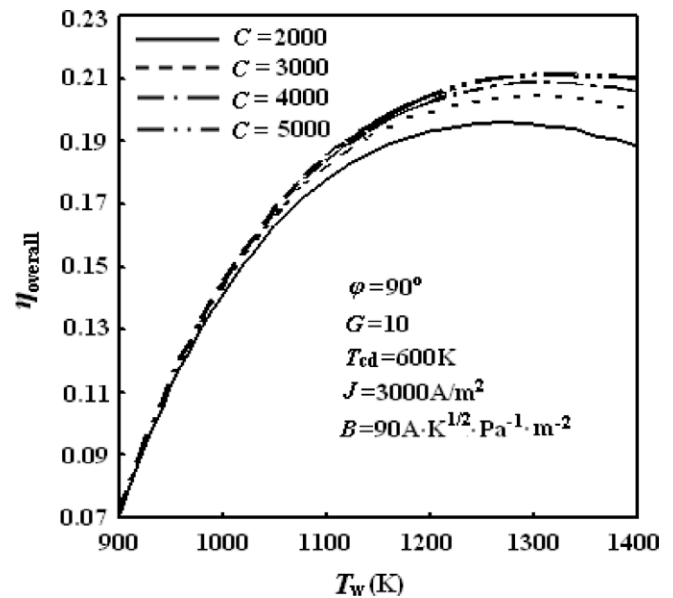
The calculated effects of varying operating temperature T_w on η_c , η_{AMTEC} , and $\eta_{overall}$ of the parabolic dish/AMTEC system are shown in Fig. 3. As expected, for the solar collector subsystem, the higher the operating temperature T_w , the lower the collector efficiency η_c , and η_c decreases almost linearly with increasing T_w . On the other hand, η_{AMTEC} increases evidently with increasing T_w , which is also the operating temperature of AMTEC subsystem. However, when T_w increases to a relatively large value, the increasing rate of η_{AMTEC} begins to level off. As a result, these two opposite effects cause $\eta_{overall}$ of the parabolic dish/AMTEC system to peak at 20.6% when the operating temperature $T_w = 1280$ K for the given conditions. However, the efficiency curve near the peak is relatively flat, thus it is preferable to operate on a slightly lower temperature, for example, $T_w = 1200$ K, at the expense of a small decrease in $\eta_{overall}$ (only 0.5% decrease of $\eta_{overall}$, from 20.6% for $T_w = 1280$ K to 20.1% for $T_w = 1200$ K).

As shown in Figs. 4 and 5, calculated results are presented to assess the effects of geometric concentration ratios C and tilting angle of cavity ϕ on $\eta_{overall}$ for the parabolic dish/AMTEC system. Fig. 4 shows the $\eta_{overall}$ versus the operating temperature T_w for various C . It is obvious that the $\eta_{overall}$ increases with the increasing of C . And the peak $\eta_{overall}$ increases from 19.8% to 21.2% when C increases from 2000 to 5000. However, it is worthy to note that the

Table 4

Main parameters of the combined system.

Parameter	Symbol	Value
Dish concentrator aperture area	A_a	100 m ²
Normal direct insolation (DNI) per unit of collector area	I_s	900 W/m ²
Factor of un-shading	λ	0.99
Reflectivity of dish surface	ρ	0.94
Transmittance–absorptance product	$\tau\alpha$	0.9
Intercept factor of receiver	γ	0.99
Aspect ratio of cavity	H/D	0.25
Radiative emissivity of cavity	ε_c	0.9
Radiative emissivity of BASE	ε_b	0.9
Radiative emissivity of condenser surface	ε_{cd}	0.02
Ambient temperature	T_a	298 K

**Fig. 3.** Variations of $\eta_{overall}$, η_c and η_{AMTEC} with T_w .**Fig. 4.** Variations of $\eta_{overall}$ with T_w having C as a parameter.

effect of C is negligible when T_w is relatively low. Conversely, the influence of C becomes more significant when T_w is higher, due to that the parasitic heat losses from the receiver aperture is dominant at a high value of T_w . Fig. 5 describes $\eta_{overall}$ for the parabolic dish/AMTEC system as function of T_w , when $\phi = 0^\circ, 30^\circ, 60^\circ, 90^\circ$, respectively. It can be observed that the $\eta_{overall}$ increases with the increasing of ϕ . The $\eta_{overall}$ is the smallest when $\phi = 0^\circ$, while the $\eta_{overall}$ reaches the greatest value when $\phi = 90^\circ$. This trend is to be expected since as the inclination of receiver increases, more high temperature buoyant air remains stagnant within the cavity of the receiver. The maximum convection loss occurs at $\phi = 0^\circ$ where it corresponds to the peak $\eta_{overall}$ of 18.9%, and the convection loss reduces to a minimum at $\phi = 90^\circ$ where the corresponding peak $\eta_{overall}$ is 20.6%. Similar to Fig. 4, the influence of ϕ on $\eta_{overall}$ becomes more considerable with the increase of T_w .

Fig. 6 illustrates the variations of $\eta_{overall}$ with T_w for different values of T_{cd} . All the curves show similar dependence on T_w for

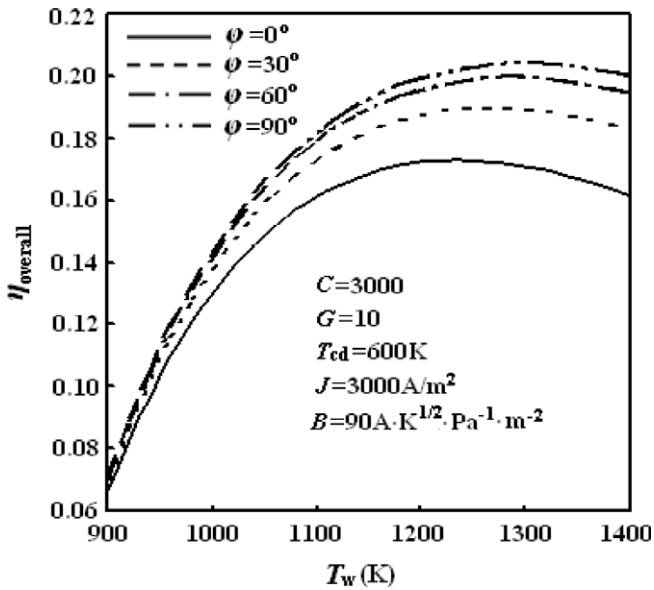


Fig. 5. Variations of η_{overall} with T_w having ϕ as a parameter.

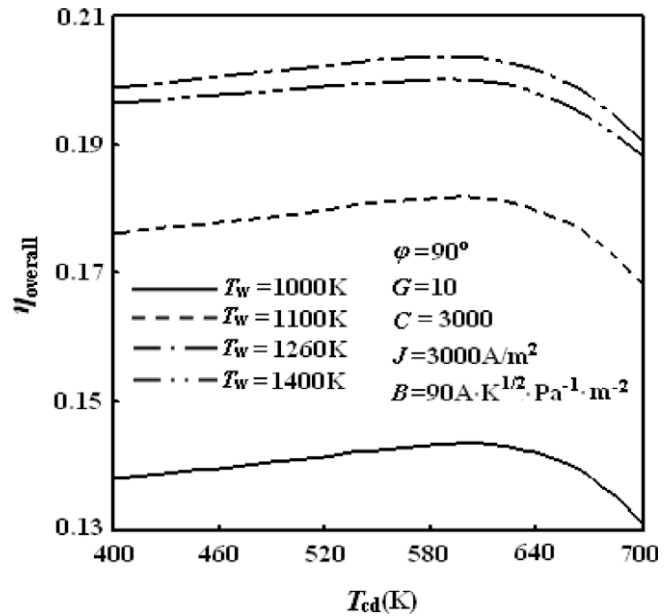


Fig. 7. Variations of η_{overall} with T_{cd} having T_w as a parameter.

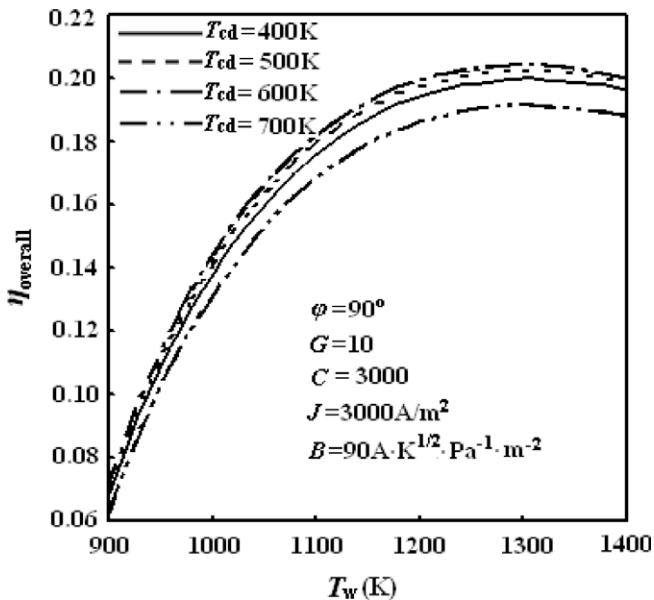


Fig. 6. Variations of η_{overall} with T_w having T_{cd} as a parameter.

the η_{overall} of the parabolic dish/AMTEC system. It is evident that the η_{overall} increases first, and then drops down as the T_{cd} varies from 400 K to 700 K. The peak values for η_{overall} varies, as the curves show that the peak η_{overall} is 20.1%, 20.4%, 20.6%, and 19.2% when T_{cd} is 400 K, 500 K, 600 K and 700 K, respectively. The present results suggest that there exists an optimum value of T_{cd} for the maximum η_{overall} . This can be seen more clearly in Fig. 7, where each curve in this figure has a peak point that represents the maximum η_{overall} corresponding to an optimal value of T_{cd} . This is expected, because radiation heat loss from the BASE elements to the condenser walls of the AMTEC decreases as the condenser temperature increases. Meanwhile, an increase in condenser temperature causes the voltage and the electrical power output of the AMTEC to decrease. The combined effects make the η_{overall} for the parabolic dish/AMTEC system peak at around $T_{cd} = 600$ K, as shown in Fig. 7.

However, when T_{cd} is less than 600 K, the increment tendency of η_{overall} with T_{cd} is quite slow. This is due to the fact that, below $T_{cd} = 600$ K, the condenser saturation pressure is very small and essentially negligible compared to the pressure drop in the low-pressure region of the AMTEC. When T_{cd} increases, the pressure at the BASE/cathode interface increases slowly, thus the voltage and power output of the AMTEC decreases slowly, causing a slow-motion of η_{overall} increment. While T_{cd} is greater than 600 K, a sharp drop in η_{overall} with T_{cd} is observed, which is explained as follows: above 600 K, the condenser saturation pressure increases exponentially with T_{cd} , and the pressure at the BASE/cathode interface increases rapidly with increasing T_{cd} , causing the voltage and the electrical power output of the AMTEC to decrease. Therefore, the decrease in heat losses and heat input to the converter as T_{cd} increases, in conjunction with the decrease in AMTEC electrical power output, leads to the different varying tendency of η_{overall} with T_{cd} for the solar thermal power system when T_{cd} is less or greater than 600 K, as shown in Fig. 7. It should be pointed out that the efficiency curve near the peak is very flat, thus for the purpose of recycling the exhaust heat from the condenser (including the radiation heat loss and the latent heat released by the sodium vapor), a relatively high condenser temperature is recommended. In addition, it is interesting to note that the optimal value of T_{cd} is always near 600 K when T_w varies, indicating that the optimal value of T_{cd} is not strongly related to T_w .

The influence of dimensionless geometric pressure loss coefficient G on η_{overall} for the parabolic dish/AMTEC system is investigated in Fig. 8. An increase in G results in a decrease in η_{overall} , which is contributed to the fact that increasing dimensionless geometric pressure loss coefficient G means more concentration loss in the cathode sides of the BASE elements, which causes decreasing in the output of electrical power. It also can be seen that the η_{overall} decreases dramatically with the increasing of G when G is of small values. When G is larger, the η_{overall} continues to decrease, but with slower decreasing rate.

The results are presented in Fig. 9 for illustrating the impact of the temperature-independent charge-exchange coefficient B on η_{overall} for the parabolic dish/AMTEC system. It is shown that the η_{overall} gradually increases with the increasing of B . This trend is not doubtful, because the temperature-independent charge-exchange coefficient B is a measurement of the contact between

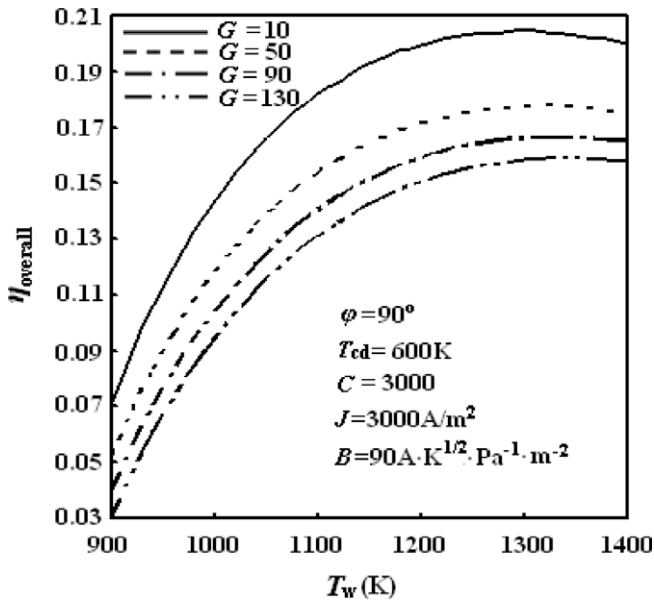


Fig. 8. Variations of η_{overall} with T_w having G as a parameter.

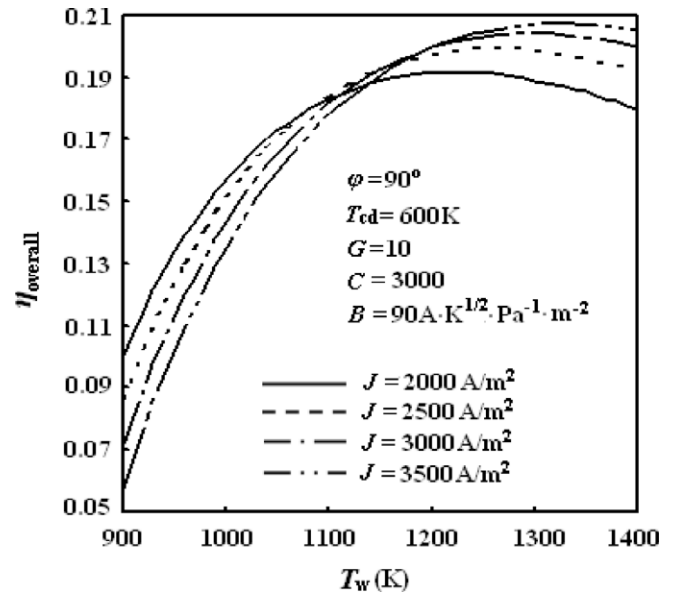


Fig. 10. Variations of η_{overall} with T_w having J as a parameter.

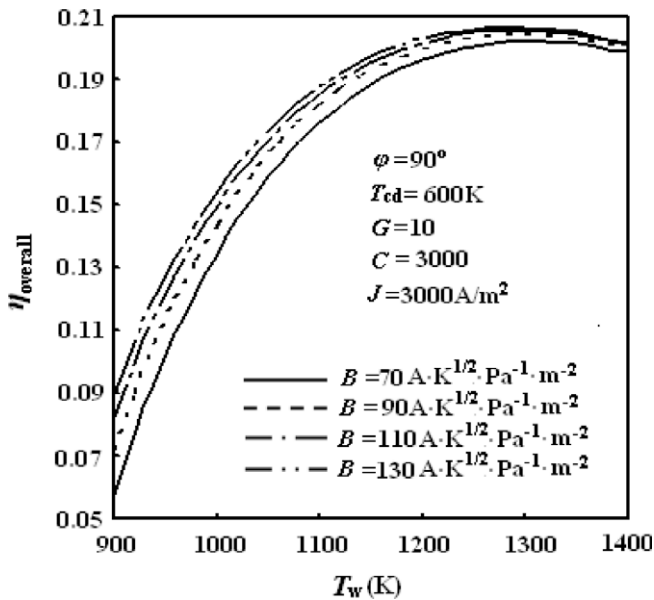


Fig. 9. Variations of η_{overall} with T_w having B as a parameter.

electrode and BASE. However, the effect of B becomes negligible when the operating temperature T_w is relatively high, which is unlike the trend in Figs. 4 and 5. A larger value of B means less internal charge-exchange polarization losses, thus higher value of η_{overall} . This can be met by high performance electrodes, such as Rh_xW refractory electrodes (where x varies between 1 and 2) [46,47].

The predicted effects of varying current density J on η_{overall} for the parabolic dish/AMTEC system are presented in Fig. 10. It is found that the variations of η_{overall} with T_w for various J are quite different from those figures shown above. The curves for varied J in this figure cross to each other. When T_w is relatively small (<1100 K), the lower the current density J , the higher the η_{overall} . On the contrary, when $T_w > 1100$ K, the higher the current density J , the higher the η_{overall} .

Finally, Table 5 has been presented to summarize the findings of the parametric analysis.

6. Conclusions

In this study, a new parabolic dish/AMTEC solar thermal power system is proposed. The proposed system is an attractive solar thermal power system that has many advantages over the existing dish/engine systems. Moreover, this new system has employed a separate type heat-pipe receiver, in which the solar energy is isothermally transferred from the dish to the AMTEC. This type of receiver makes it convenient and flexible to lay out the components of system. The thermal-electric conversion performance of this combined system has been theoretically investigated by modeling and calculating its overall conversion efficiency. Results show that the overall thermal-electric conversion efficiency of parabolic dish/AMTEC system peaks at 20.6% with power output of 18.54 kW corresponding to an operating temperature of 1280 K. Considering the passive nature of the system, the parabolic dish/AMTEC system has the potential to become one of the least expensive sources of renewable energy.

The relationship between the overall thermal-electric conversion efficiency of the parabolic dish/AMTEC system and various parameters has been discussed in detail. Parameters analysis shows that, for the solar collector subsystem, increasing both geometric concentration ratio and tilting angle of the receiver would increase the overall efficiency of the combined system. The overall efficiency of parabolic dish/AMTEC system can also be improved by increasing the temperature-independent charge-exchange coefficient or decreasing dimensionless geometric pressure loss coefficient in the AMTEC subsystem. This improvement can be realized by design optimizations. The varying current density has distinct effect on overall efficiency of the parabolic dish/AMTEC system, namely, a lower current density leads to significantly higher system efficiency at a relatively low operating temperature, while the opposite result has been obtained at a relatively high operating temperature. The calculated results also reveal that an optimum value of condenser temperature exists for the maximum overall efficiency. Furthermore, the maximum overall efficiency corresponds to a relatively high condenser temperature (about 600 K), which means that it is practical and cost-effective to recycle the exhaust heat, thus to further enhance the system efficiency.

Table 5

A summary of the parametric analysis findings.

Parameters	Influence on η_{overall}
T_w	(o): η_{overall} increases and then decreases, which resulting a peak value of 20.6% at the operating temperature $T_w = 1280$ K for the given conditions
C	(+): η_{overall} increases with the increasing of C , and the effect is more significant when T_w is higher
ϕ	(+): η_{overall} increases with the increasing of ϕ , and the effect is more considerable with the increase of T_w
T_{cd}	(o): η_{overall} increases first, and then drops down as T_{cd} varies from 400 K to 700 K, suggesting an optimum value of $T_{cd} = 600$ K for the maximum η_{overall}
G	(–): η_{overall} decreases with the increasing of G ; when G is larger, the η_{overall} continues to decrease, but with slower decreasing rate
B	(+): η_{overall} increases with the increasing of B , but the effect of B becomes negligible when T_w is relatively high
J	(–): When $T_w < 1100$ K, η_{overall} decreases with the increasing of J (+): When $T_w > 1100$ K, η_{overall} increases with the increasing of J

Note: (+) means η_{overall} is an increasing function of the parameter.(–) means η_{overall} is an decreasing function of the parameter.(o) means η_{overall} peaks at an optimal value of the parameter.

References

- [1] Kalogirou SA. Solar thermal collectors and applications. *Prog Energy Combust Sci* 2004;30(3):231–95.
- [2] Schwarzbözl P, Buck R, Sugarmen C, Ring A, Jesús Marcos Crespo M, Altwegg P, et al. Solar gas turbine systems: design, cost and perspectives. *Sol Energy* 2006;80(10):1231–40.
- [3] Shinnar R, Citro F. Solar thermal energy: the forgotten energy source. *Technol Soc* 2007;29(3):261–70.
- [4] Montes MJ, Abánades A, Martínez-Val JM. Performance of a direct steam generation solar thermal power plant for electricity production as a function of the solar multiple. *Sol Energy* 2009;83(5):679–89.
- [5] Yang M, Yang X, Yang X, Ding J. Heat transfer enhancement and performance of the molten salt receiver of a solar power tower. *Appl Energy* 2009, doi:10.1016/j.apenergy.2009.04.042.
- [6] Klais H, Kohne R, Nitsch J, Sprengel U. Solar thermal power plants for solar countries—technology, economics and market potential. *Appl Energy* 1995;52(2–3):165–83.
- [7] Mancini TR, Kolb GJ, Chavez JM. Solar thermal power today and tomorrow. *Mech Eng* 1994;116(8):74–9.
- [8] Ravi Kumar K, Reddy KS. Thermal analysis of solar parabolic trough with porous disc receiver. *Appl Energy* 2009;86(9):1804–12.
- [9] Mancini T, Heller P, Butler B, Osborn B, Schiel W, Goldberg V, et al. Dish-stirling systems: an overview of development and status. *J Sol Energy Eng* 2003;125(2):135–51.
- [10] Karabulut H, Yücesu HS, Çınar C, Aksoy F. An experimental study on the development of a β -type Stirling engine for low and moderate temperature heat sources. *Appl Energy* 2009;86(1):68–73.
- [11] Washom B. Parabolic dish Stirling module development and test results. Paper No. 849516. In: Proceedings of the 19th IECEC, San Francisco, CA; 1984.
- [12] Sandia. Stirling energy systems set new world record for solar-to-grid conversion efficiency. 2008. Available from: <http://www.newswise.com/articles/view/537732/?sc=whn>.
- [13] Bonnet S, Alaphilippe M, Stouffs P. Thermodynamic solar energy conversion: reflections on the optimal solar concentration ratio. *Int J Energy Environ Econ* 2006;12(3):141–52.
- [14] El-Genk MS, Tournier JM. AMTEC/TE static converters for high energy utilization, small nuclear power plants. *Energy Convers Manage* 2004;45(4):511–35.
- [15] Levy GC, Hunt TK, Sievers RK. AMTEC: current status and vision. In: Proceedings of the 32th intersociety energy conversion engineering conference, vol. 2; 1997. p. 1152–5.
- [16] Cole T. Thermoelectric energy conversion with solid electrolytes. *Science* 1983;221(4614):915–20.
- [17] US Department of Energy, Nuclear Energy Research Initiative. Novel, integrated reactor/power conversion system (LMR-AMTEC), Project Number: 99-0198, Research Grant Number: DE-FG03-99SF21987. Final Scientific/Technical Report, Report Number: STD-ES-03-04, March 31; 2003.
- [18] Leibfried U, Ortjohann J. Convective heat loss from upward and downward-facing cavity receivers: measurements and calculations. *ASME J Sol Energy Eng* 1995;117:75–84.
- [19] Reddy KS, Kumar NS. Combined laminar natural convection and surface radiation heat transfer in a modified cavity receiver of solar parabolic dish. *Int J Therm Sci* 2008;47(12):1647–57.
- [20] Tournier JM, El-Genk MS. Performance analysis of pluto/express, multitube AMTEC cells. *Energy Convers Manage* 1999;40(2):139–73.
- [21] Diver RB, Andraka CE, Moreno JB, Adkins DR, Moss TA. Trends in dish-stirling solar receiver design. In: Proceedings of the 25th intersociety energy conversion engineering conference, vol. 5; 1990. p. 303–10.
- [22] Angelino G, Invernizzi C. Binary conversion cycles for concentrating solar power technology. *Sol Energy* 2008;82(7):637–47.
- [23] Kribus A, Kaftori D, Mittelman G, Hirshfeld A, Flitsanov Y, Dayan A. A miniature concentrating photovoltaic and thermal system. *Energy Convers Manage* 2006;47(20):3582–90.
- [24] Feuermann D, Gordon JM. High-concentration photovoltaic designs based on miniature parabolic dishes. *Sol Energy* 2001;70(5):423–30.
- [25] Alaphilippe M, Bonnet S, Stouffs P. Low power thermodynamic solar energy conversion: coupling of a parabolic trough concentrator and an Ericsson engine. *Int J Thermodyn* 2007;10(1):37–45.
- [26] Segal A, Epstein M. Optimized working temperatures of a solar central receiver. *Sol Energy* 2003;75(6):503–10.
- [27] Palavras I, Bakos GC. Development of a low-cost dish solar concentrator and its application in zeolite desorption. *Renew Energy* 2006;31(15):2422–31.
- [28] Taebeom SEO, Siyoul RYU, Yonheock KANG. Heat losses from the receivers of a multifaceted parabolic solar energy collecting system. *KSME Int J* 2003;17(8):1185–95.
- [29] Le Quere P, Penot F, Mirenayat M. Experimental study of heat loss through natural convection from an isothermal cubic open cavity. Sandia National Laboratories Report, SAND81-8014; 1981.
- [30] Koenig AA, Marvin M. Convection heat loss sensitivity in open cavity solar receivers. Final report, DOE Contract No: EG77-C-04-3985, Department of Energy, USA; 1981.
- [31] Siebers DL, Kraabel JS. Estimating convective energy losses from solar central receivers. Sandia National Laboratories Report, SAND 84-8717; 1984.
- [32] Clausen AM, Waldvogel JM, Lister LD. Natural convection from isothermal cubical cavities with a variety of side-facing apertures. *ASME J Heat Transfer* 1987;109(2):407–12.
- [33] Stine WB, McDonald CG. Cavity receiver convective heat loss. In: Proceedings of the international solar energy society (ISES) solar world conference, Kobe, Japan; 1989.
- [34] Paitoonsurikarn S, Taumoeafolau T, Lovegrove K. Estimation of convection loss from paraboloidal dish cavity receivers. In: Proceedings of 42nd conference of the Australia and New Zealand solar energy society (ANZSES), Perth, Australia; 2004.
- [35] Taumoeafolau T, Paitoonsurikarn S, Hughes G, Lovegrove K. Experimental investigation of natural convection heat loss from a model solar concentrator cavity receiver. *ASME J Sol Energy Eng* 2004;126(2):801–7.
- [36] Wu YC, Wen LC. Solar receiver performance of point focusing collector system. ASME winter annual meeting, San Francisco, CA; 1978.
- [37] Kaushika ND, Reddy KS. Performance of a low cost solar paraboloidal dish steam generating system. *Energy Convers Manage* 2000;41(7):713–26.
- [38] Tournier JM, El-Genk MS, Schuller M, Hausgen P. An analytical model for liquid-anode and vapor-anode AMTEC converters. Space technology and applications international forum. AIP Conf Proc 1997;387:1543–52.
- [39] Weber N. A thermoelectric device based on beta-alumina solid electrolyte. *Energy Convers* 1974;14:1–7.
- [40] Williams RM, Loveland ME, Jeffries-Nakamura B, Underwood ML, Bankston CP, Leduc H, et al. Kinetics and transport at AMTEC electrodes – I. The interfacial impedance model. *J Electrochem Soc* 1990;137(6):1709–16.
- [41] Underwood ML, Williams RM, Ryan MA, Jeffries-Nakamura B, O'Connor D. An AMTEC vapor–vapor, series connected cell. Proceedings of the 9th symposium on space nuclear power systems. AIP Conf Proc 1992;246:1331–7.
- [42] Tournier JM, El-Genk MS. An electric model of a vapor anode, multi-tube alkali-metal thermal-to-electric converter. *J Appl Electrochem* 1999;29(11):1263–75.
- [43] Steinbrück M, Heinzel V, Huber F, Peppeler W, Hill H, Voss M. Investigations of beta-alumina solid electrolytes for application in AMTEC cells. In: Proceedings of the 28th intersociety energy conversion engineering conference, vol. 1; 1993. p. 780–99.
- [44] Siegel R, Howell JR. Thermal radiation heat transfer. 2nd ed. New York: Hemisphere; 1981.
- [45] Paitoonsurikarn S, Lovegrove K. Numerical investigation of natural convection loss in cavity-type solar receivers. In: Proceedings of 40th conference of the Australia and New Zealand solar energy society (ANZSES), Newcastle, Australia; 2002.
- [46] Ryan MA, Shields VB, Cortez RH, Lara L, Homer ML, Williams RM. Lifetime of AMTEC electrodes: molybdenum, rhodium–tungsten, and titanium nitride. Space technology and applications international forum. AIP Conf Proc 2000;504:1377–82.
- [47] Ryan MA, Williams RM, Lara L, Liebig BG, Cortez RH, Kisor AK, et al. Advances in electrode materials for AMTEC. Technology and applications international forum. AIP Conf Proc 2001;552:1088–93.